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Effects of Tablet Display Colors on Prefrontal Lobe Activation in Elderly People

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The use of information and communication technology (ICT) devices has been spreading in many scenes in the daily life of elderly people, and a tablet computer has been considered as a useful tool to help them enhance their quality of life (QOL). In this study, we investigated how the colors displayed on a tablet screen affect the activation of the frontal lobe of elderly people while they are performing tasks on the tablet. Two experiments were conducted for concentration and memory tasks by using different display colors, and the oxygenated hemoglobin concentration changes in the brain region of elderly subjects were measured by near-infrared spectroscopy, which is a method of measuring the level of oxygenation in the blood flowing through the tissue with a near infrared light source and a light receiving sensor. The experimental results showed the following effects of display colors on the prefrontal cortex of elderly people: 1) green display color can enhance the activation of the prefrontal lobe, and 2) in the case of a simple task, the use of a display color with a high contrast ratio against black can induce the activation of the prefrontal lobe. These results can be utilized to improve ICT screen designs for elderly people to enhance their brain activation, which is closely related to the improvement of their QOL and sense of well-being.

1. Introduction

The use of information and communication technology (ICT) devices has been spreading in many scenes in the daily life of elderly people. The number of people aged 65 years and over who use digital devices such as a smartphone and a tablet computer has grown in the past decade.[1] In particular, a tablet computer is considered to be a useful tool for them because of its portability and light weight. Also, its larger screen is easier on older eyes and requires less scrolling than a smart phone.[2] A study by Chatrangsan and Petrie showed that elderly people

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had positive attitudes towards tablet computers.[3] Many studies reported the advantages of tablet computers in clinical uses for elderly people.[2,4] Furthermore, a tablet computer can be a useful tool for elderly adults to perform training or exercises to prevent mental decline and to increase their quality of life (QOL).[5–8] Since vision and concentration are known to decline with advancing age, the designs of tablet screens should be considered more carefully for elderly people.[9] Many studies have examined the visual effects of tablet screen designs on elderly people, particularly readability and usability factors.[10] Although screen designs are often discussed in terms of enhancing the QOL of elderly people, not many studies have investigated tablet screen designs in relation to brain activation, which influences their cognitive function and sense of well-being.

Some previous studies have revealed the color effects of an ICT screen on task performance and brain activation. Hall and Hanna pointed out that greater contrast ratios between background and font colors can improve the readability of a web page.[11] A study of color effects on cognitive task performances by Mehta and Zhu indicates that the task performance can be affected by background colors.[12] Since relationships between the brain activity and the color effects of an ICT screen were not investigated in those studies, the authors examined whether the brain activation in young and elderly people are related to screen colors, color preference, task performance, and feelings about readability in our previous studies of display colors of a tablet computer.[13,14]

A study by Yasumura *et al*. suggested a relationship between the performance scores of an oral reading span test and the activation of the prefrontal region of subjects whose ages ranged from 22–46 years.[15] On the other hand, the results of our studies with elderly people did not show a significant correlation between subjects' brain activation and their task performance.[14] Also, our study results did not show any significant relationship between the activation of their prefrontal lobe and their color preferences. However, we found that the colors of a tablet screen had affected the function of the prefrontal lobe of elderly subjects.[13,14] Our study results also suggest that the combination of a display color and a font color with lower readability can increase the activation of the prefrontal lobe. In addition, the results indicate that the contrast ratios to black font can be related to the activation of the prefrontal lobe.[14] These results of our studies raised the possibility of activating the prefrontal lobe of elderly people by using different display colors on a tablet screen rather than a white screen, which is often used on ICT screens to imitate a white sheet of paper.

In this study, the authors conducted two experiments to investigate how the contrast between a display color and the color of figures or letters on a tablet screen affects the brain activity of elderly people, in particular, the oxygenation of the prefrontal cortex. This part of the brain is known to be associated with memory, attention, judgment, and other critical functions.[16,17] The changes in the flow of oxygenated blood in the prefrontal cortex are related to these functions that are associated with the QOL of elderly people.[18,19] The results of many neurological studies show that decreased flow of oxygenated blood in the prefrontal cortex can cause the decline of cognitive functions.[18–22] Therefore, we focused on the changes in the oxygenated blood flow in the prefrontal area of elderly people to identify how display colors of a tablet screen affect their brain activation while they are using a tablet computer.

2. Methodologies

In the experiments, elderly subjects were given tasks to be performed on a tablet computer. A Lenovo YOGA2 tablet computer with a screen size of 10.1 inches (1920 by 1200 pixels) was used for both experiments. To have the subjects perform the tasks under the conditions of different contrast combinations, the tasks were presented on the screen with different screen colors while all figures and letters of tasks were shown in black. In the first experiment, a simple circle-counting task (CCT) was assigned to the subjects. In the second experiment, the authors adopted a more complex task, a reading span task (RST), which has been widely adopted for investigations of working memory and cognitive processing.

All the subjects were healthy adults aged 65 years or older and none of them was reported to have any color vision impairment at the time of the experiment. The authors explained the purpose and procedure of the study to the subjects and obtained their written consent to participate before the experiments. None of the subjects experienced any difficulties during the experiment. All subjects performed both CCT and RST tasks in random orders to avoid bias in the data acquisition. In both experiments, the task performance scores of each subject were recorded. While each subject was working on the tasks, the authors measured the relative changes in blood hemoglobin (Hb) concentration in the prefrontal cortex of the brain by using a brain imaging system, near-infrared spectroscopy (NIRS). This study was approved by the Research Ethics Committee of Shibaura Institute of Technology (No. 16-017).

Electroencephalography (EEG) and NIRS have been widely used as noninvasive techniques to measure changes in brain activity, including activity in the frontal lobe. In this study, we chose NIRS for the following reasons. Many studies mention that EEG measurements can be affected by electrical signals from electronic devices.(23) In the CCT and RST experiments, the subjects perform tasks on a tablet computer, which can cause electrical interference of the EEG measurements. On the other hand, NIRS measurements are unaffected by such electrical signals from the tablet computer. In addition, NIRS offers measurement data with better spatial resolution and fewer artifacts from the body movement of subjects compared with data from EEG measurement.(24)

2.1 NIRS systems

NIRS is an optical technique that can measure brain tissue oxygenation and hemodynamics in real time. In a NIRS system, a light source and a light-receiving sensor are placed to visualize which part of the brain has undergone an activity change. The light source emits near-infrared light, which can penetrate to a depth of 2 or 3 cm from the brain scalp, from an emission probe. According to the oxygenated Hb (oxy-Hb) and Hb concentration rates in the blood, the light is absorbed or scattered before the light is detected by a paired detection sensor (light-emitting probe and detection sensor; Probe 13 and Probe 14, respectively, in Fig. 1). The extent of the scattering and absorption of this infrared light is then measured as NIRS signals of a channel between the probes (Channel 6 in Fig. 1). An increase in NIRS signal values from the channel is

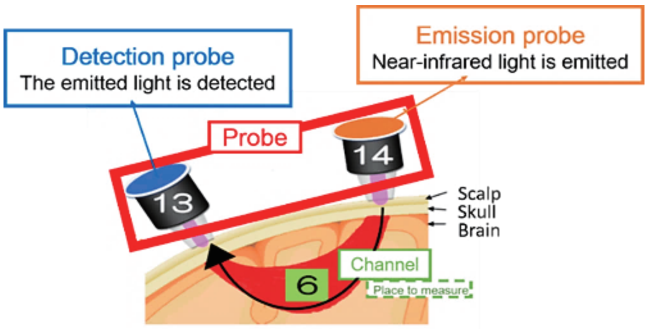

Fig. 1. (Color online) NIRS probes and how the probe detects near-infrared light [redrawn based on Fukuda[25]].

interpreted as the activation of the brain region covered by the channel. In this study, two types of wearable NIRS system by NeU, WOT-100 and HOT-2000, were used to measure blood Hb concentration changes in the subject's prefrontal lobe.

2.2 Experiment with a CCT

A task of counting one type of figure among other types of figure is often used to test the attention and concentration levels of children and elderly people. The subjects were asked to count the number of circles randomly placed among triangles and squares on the tablet screen with four different background colors: the primary colors for computer screens (red, green, and blue) and white. In Table 1, the characteristics of the screen colors, such as contrast ratios against the black figures used in the experiment, are summarized. The test set for each background color consisted of ten CCT questions. A subject chose his/her answer by tapping one button from among four choices displayed on the screen. All the task pages had the same design with three types of figure (circles, triangles, and squares), and the black buttons presented against a single-color background. The duration was set to 30 s for one circle-counting page. Figure 2 shows an example of the task pages on a white background.

Ten native Japanese elderly people (aged from 65 to 75, seven males, three females) participated in the CCT experiment. They counted the number of circles among the other figures and choose the answer by touching one of four choices on the screen within a short period. While each subject was counting the circles, the oxygenated Hb concentration changes in his/her prefrontal cortex were recorded using a wearable NIRS (NeU WOT-100, 16 channels). Figure 3 shows a picture of a female subject wearing the NIRS probes while performing the CCT tasks.

2.3 Experiment with a RST

In this experiment, the authors adopted RSTs designed by Osaka for Japanese subjects.[26] RSTs are widely used as a task for assessing short-term memory capacity. An RST involves verbal processing and requires more complex brain processes than the CCT task used in the first experiment. The authors adopted RSTs, expecting a more complex task than the CCT task to

Table 1
(Color online) Hexadecimal code, color hue, and contrast ratio to black of four background colors used in the CCT experiment.

Background color	Hexadecimal code	Color Hue (degree)	Contrast Ratio to Black
White	#FFFFFF	0	21
Yellow	#FFFF00	60	19.55
Red	#FF0000	0	5.25
Green	#00FF00	120	15.3
Blue	#0000FF	240	2.44

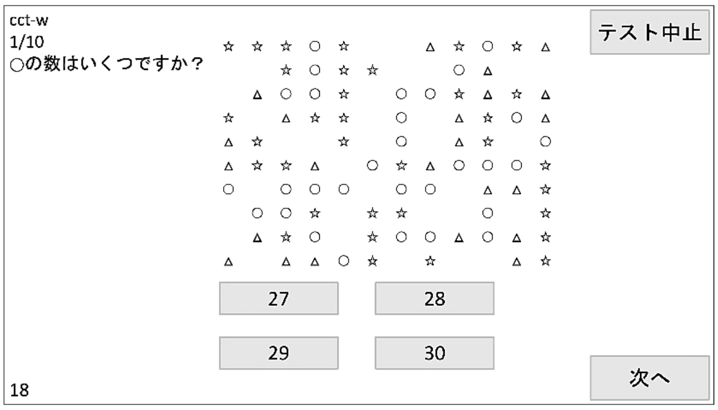

Fig. 2. Example of a CCT task page.

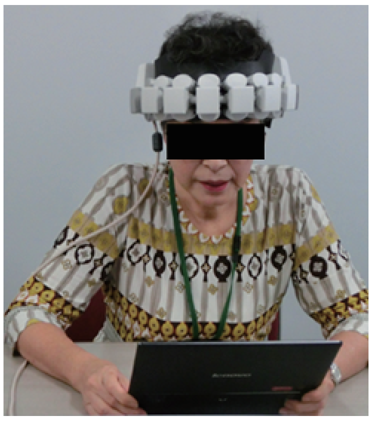

Fig. 3. (Color online) Subject wearing the NIRS probes while performing the CCT tasks

provoke clearer changes in the activities of the prefrontal cortex. On the basis of the results of our previous RST experiment with young and elderly subjects, the authors focused on the contrast effects of screen colors in this experiment.[13] Three colors that are often used as screen colors on an ICT screen (white, blue, and green) were chosen as the base colors. Then, two screen colors with different contrasts for each basic color were adopted (white and gray, light green and dark green, light blue and dark blue). The Japanese sentences in RST tasks were presented in black on the screen. Table 2 shows the characteristics of each color such as its contrast ratio against the black font used in the experiment.

Six sets of RSTs for each background color were developed, and each test set consisted of five levels of RST questions. Each level consisted of a different number of sentences, starting with two sentences for the first level and increasing one additional sentence in each consecutive level. A total of 20 sentences were presented in one set. All the task pages had the same design with each sentence displaying one underlined word in black font against a single-color background. One sentence was displayed at a time. The subjects were asked to memorize the underlined word while reading each sentence aloud in 6.5 s and to recall the underlined words aloud within a short period. There was no rule for the order of the words recalled. As a resting task, a blank white page appeared at every interval for 10 s between RST sentence pages with the respective screen colors A total of 67 sentences were obtained from Japanese RST sentences listed in Osaka.(26) Figure 4 shows an example of the task pages on the white background. Six native Japanese elderly people (aged from 67 to 77, four males, two females) participated in the RST experiment. The total Hb concentration changes in the prefrontal cortex of each subject were recorded by using a wearable NIRS (NeU HOT-2000, 2 channels) while the subject read the sentences, memorized the underlined words, and recalled the words. Figure 5 shows a female subject wearing the NIRS probes while performing the RST tasks.

We did not use the yellow or red screen color for the RST experiment for the following reasons. A brain measurement experiment for long periods of time often imposes strain on

Table 2
(Color online) Hexadecimal codes, color hues, and contrast ratios to black of six background colors used in the RST experiment.

Display color	Hexadecimal code	Color Hue (degree)	Contrast Ratio to black
White	#FFFFFF	0	21
Gray	#C2C2C2	0	11.78
Light Green	#76FF76	120	16.33
Dark Green	#008900	120	4.57
Light Blue	#7676FF	240	5.8
Dark Blue	#000089	240	1.36

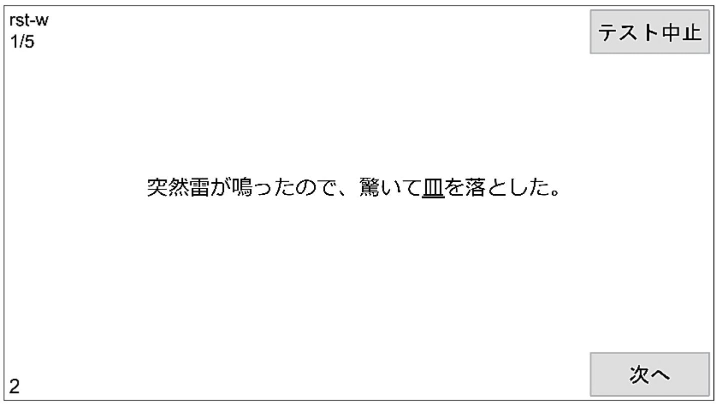

Fig. 4. Example of an RST task page.

Fig. 5. (Color online) Subject wearing the NIRS probes while performing the RST tasks.

elderly subjects, which can interfere with the measurement of brain activity. Therefore, we reduced the number of colors to three (white, green, and blue) for the RST, rather than five in the CCT. Some studies of color sensitivity of elderly people have revealed that the visual recognition of elderly people decreases more for blue and green than yellow and red.[27,28] In this experiment, we decided to focus on the contrast effects of only green and blue, which are expected to produce more stress but are also used more often as a screen color than yellow and red.

3. Results and Analysis

3.1 Task Performance for CCT and RST tasks

The CCT performance of each subject was determined on the basis of the number of questions answered correctly. With 10 CCT questions for each background color, the highest score for the test set of each color would be 10. The average percentage of scores of all the subjects for each background color was calculated and summarized as a percentage in Table 3. As Table 3 shows, the subjects performed best (perfect score) with the white background color, but worst with the yellow background. The differences in the averaged performance scores were not significant among the background colors. Also, no significant correlation was observed between CCT performance and the hue value of the display color.

The RST performance score of each subject was determined on the basis of the total number of words correctly recalled. A total of 20 sentences would give 20 as the highest score for the test set of each background color. The average score (%) for questions answered correctly for each background color was calculated and summarized in Table 3. As Table 3 shows, the subjects performed best with the white background color, and worst with the dark blue background among all the background colors. Even though the difference was not significant, the RST performance score was higher for the high-contrast color than for the low-contrast color of each base color (white > gray, light blue > dark blue, light green > dark green). As in the case of CCT tasks, there was no significant correlation between RST performance and the hue values of the five display colors.

Table 3
(Color online) Average performance score for each display color in CCT and RST (%).

Display color	CCT (N = 10)
White	100
Yellow	94.29
Red	98.57
Green	97.14
Blue	98.57

Display color	RST (N = 6)
White	58.33
Gray	54.67
Light Green	55.00
Dark Green	52.50
Light Blue	55.00
Dark Blue	45.83

3.2 NIRS signal analysis

Since the activation of the prefrontal cortex was the focus of this study, the authors analyzed NIRS signal values as the changes in the flow of oxygenated blood in the whole region of the prefrontal cortex. The measurement values for each NIRS channel were not analyzed in detail. For the CCT tasks, the NIRS signals obtained during the steps of counting circles on the pages for questions 1 to 10 were subjected to the analysis. For the RST tasks, the NIRS signals obtained during the steps from memorizing to recalling the underlined words were subjected to the analysis. The signal values obtained by the NIRS system indicate relative changes in oxygenated/total hemoglobin concentration, not absolute values. Therefore, it is not possible to directly determine the average value across subjects or channels. To obtain averages across subjects or channels, a standardization procedure is necessary.[29] Also, NIRS signals cannot be directly compared between subjects because of biological fluctuations in the skin blood flow. Therefore, the signals were standardized by z-score normalization.[29]

The standardization was performed using Eq. (1) below.[15] This procedure has been used in many studies for data collected from a small number of subjects, particularly NIRS experiments with children and elderly people. We averaged the z-scores from all the channels for all the subjects for the CCT and RST experiments.

$$z = \frac{NIRS\,signal(t) - \mu_{Rest}}{\sigma_{Rest}} \tag{1}$$

Here, *NIRS signal* (t) represents the NIRS signal value at each measurement time t (every 0.1 s). In Eq. (1), μ_{Rest} is the average of NIRS signal values and σ_{Rest} is the standard deviation of NIRS signal values during the resting periods.

3.2.1 NIRS signal result of CCT experiment

Figure 6 shows the z-score of NIRS signal values of each screen color for the CCT. The z-score was the highest for the yellow background color and the lowest for the blue background. A negative score implies a decrease in oxygenated blood flow. As shown in Fig. 6, the z-scores of yellow, green, red, and blue backgrounds were in the descending order of the contrast ratios of these colors to black, which was used for all the shapes on the screen. The z-scores of these

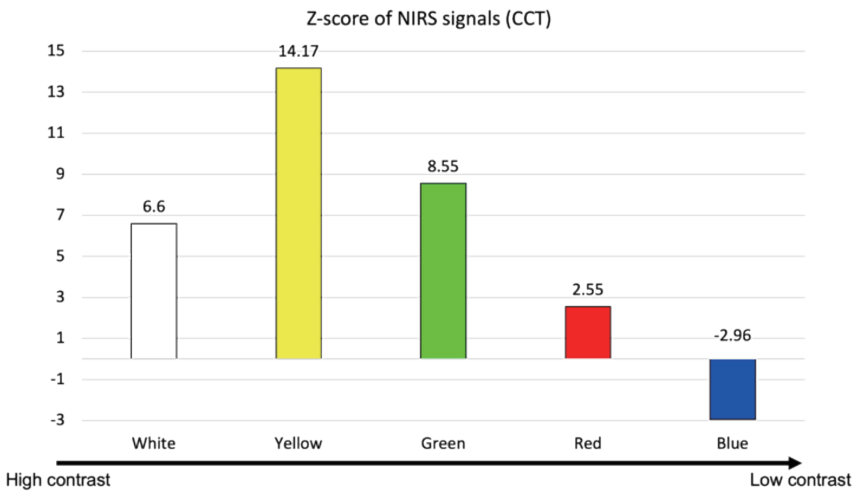

Fig. 6. (Color online) *Z*-score of NIRS signal values for each background color in the CCT experiment.

colors showed a high correlation of 0.86 to the contrast ratios. On the other hand, no significant relations were observed between the hue values of the background colors and the *z*-scores for the CCT tasks.

3.2.2 NIRS signal result of RST experiment

Figure 7 shows the *z*-score of NIRS signal values for each background color for the RST. The *z*-score for dark green was the highest, followed by that for light green. Lower *z*-scores were observed with both light blue and dark blue. For green and blue, the colors with lower contrast showed higher *z*-scores than those with higher contrast (dark green > light green, and dark blue > light blue). No significant relationship was observed between the hue value of the background color and the *z*-score for the RST task. To clarify the effect of different contrasts on brain activity, we divided the six screen colors into two groups on the basis of their contrast ratios to black font (Table 2): the high contrast group (white, light green, gray) had contrast ratios of more than 11, and the low contrast group (light blue, dark green, dark blue) had ratios of less than 5. The average *z*-score of the high contrast group (z = 2.93) is higher than that of the low contrast group (z = 2.65).

4. Discussion

The experimental results of NIRS measurements show that green has positive effects on brain activation. The result of the CCT experiment showed that the green screen induced higher activation of the prefrontal cortex than white, red, and blue screens. The high-luminance and low-luminance green screen colors in the RST experiment also resulted in higher activation of the brain area than in the cases of other colors. A recent study by Xia *et al*. demonstrated that a

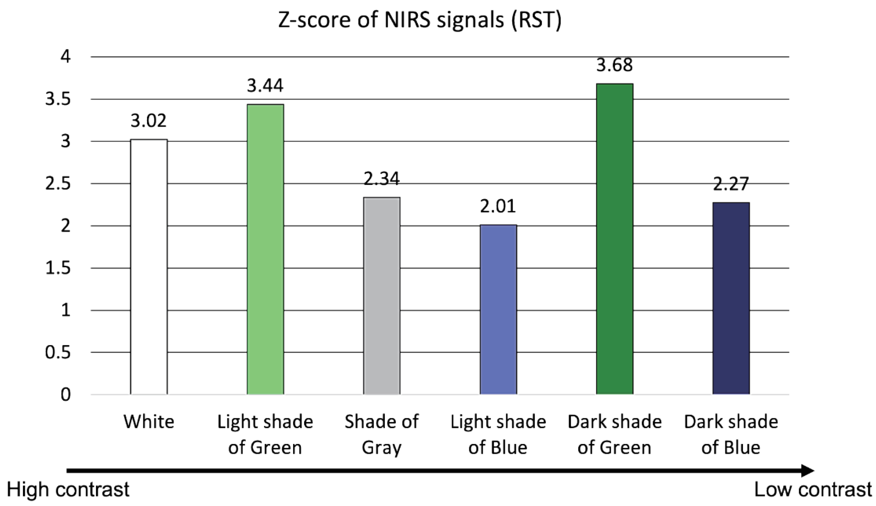

Fig. 7. (Color online) Z-score of NIRS signal values for each background color in the RST experiment.

green background enhanced the arousal levels of the subjects and led them to have lower error rates in VR environments.[30] The positive effects of green screen colors on performance and brain activation in both studies suggest that green screen colors can be used to enhance the activation of the frontal lobe of elderly people better than a white screen.

The results also suggest that the effects of color on the prefrontal cortex are affected by cognitive processes involved in a task. The RST experiment did not show the same tendency in the contrast effect as that in the CCT experiment. This is probably due to differences in task processing steps in the brain between the CCT and RST. A CCT task requires concentration but not memorization or verbal processing. An RST task, on the other hand, is more complex and involves language processing and memorization, which are associated with many brain areas, such as the inferior frontal gyrus. The higher blood flows in the brain during an RST task are probably distributed not only to the prefrontal cortex, but also to other brain areas. This may have caused lower measurement values of z-scores for the prefrontal cortex and smaller differences for the background colors in the RST experiment.

The study results did not show a clear relationship between color contrast and the percentage of correct responses. There was almost no difference in the percentage of correct responses between the maximum (100% for white) and minimum (98.75% for blue) values in the CCT experiment. The difference between the maximum (58.33% for white) and minimum (45.83% for dark blue) in the RST experiment was also insignificant. In the CCT experiment, brain activity in the prefrontal region decreased in the order of the contrast ratios of the four screen colors (yellow, green, red, and blue). However, the white screen did not activate the prefrontal cortex of the elderly subjects more than the yellow and green screens, whose contrast ratios to black are lower than white. The prefrontal cortex of the brain is known to adapt to visual stimulation of contrast change.[31] We speculate that the subjects adapted more quickly to visual stimuli from white backgrounds and showed less brain activation by the stimuli because they are “accustomed” to working on ICT screens with white screens and black fonts in their daily lives.

5. Conclusions

In this study, the authors investigated the effects of different screen colors of a tablet computer on the activation of the prefrontal cortex of elderly people. We focused on the hue and contrast ratios to black of background colors in relation to their effects on brain activation. Two different tasks on a tablet screen were adopted to see whether a simple task and a more complex task make a difference in the screen color effects on the brain, in particular, the prefrontal cortex, since blood flow in the brain region was found to decline with age.[17,18] Many neurological studies have demonstrated that lower oxygenation in the prefrontal cortex of elderly people can lead to deficient aspects of cognitive control.[18,19] Therefore, the results of this study led to the following conclusions on tablet screen colors regarding the activation of the prefrontal cortex of elderly people: 1) green screen colors can enhance the activation of the prefrontal cortex of elderly people; 2) for a simple task, the occasional use of a highly contrasted screen color, instead of white, can enhance the activation of the prefrontal cortex of elderly people.

The results of the CCT experiment showed that the frontal lobe of the elderly subjects was more activated by yellow and green than white screens, which elderly people have more occasions to work with in their daily life tasks. This indicates that unfamiliar high-contrast background colors such as yellow and green can enhance the activation of the prefrontal cortex in the case of a simple task such as circle counting. Thus, occasional insertions of an ICT page with an unfamiliar high-contrast background color among white pages can provide effective stimuli to enhance the brain activities of elderly people when they use an ICT device. In our future studies, we plan to conduct the RST experiment with yellow and red screen colors to determine whether there are different contrast effects between CCT and RST tasks.

Our previous study revealed that the brain activity of elderly people is more affected by color changes on a tablet screen than that of younger people.[13] The positive effects of green and high-contrast colors observed in this study are probably more prominent on the brain function of elderly people. Because of the acceleration of ICT uses in the daily life of elderly people, such as answering a medical questionnaire and even playing a digital game on a tablet screen, opportunities for them to work on an ICT screen will increase. Therefore, the daily use of ICT devices by elderly people should be more considered as an opportunity to enhance their brain activation. In this sense, ICT screens for elderly people should be designed from the viewpoint of their QOL enhancement. The results of this study can be utilized to improve ICT screen designs to enrich their sense of well-being.

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